Prospects for Long Pulse Operation of ArF Lasers for 193nm Microlithography

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1. Introduction

The phenomenon of compaction of fused silica is a major concern in 193nm lithography. Numerous studies have shown that as a result, the cost-of-operation of 193nm lithography is expected to be significantly higher than at 248nm due to the degradation of scanner optics. Recent studies have also shown that compaction could be reduced by increasing the pulse length of the ArF laser since the magnitude of compaction reduced as $1/(\mathrm{Tis})^{0.6}$. Here, Tis is the integral square pulse duration and is given as:

$$\mathrm{Tis} = \frac{\left(\int I(t)dt\right)^2}{\int I(t)^2 dt}$$

where I(t) is the time-dependent power of the laser pulse. Previously, investigations on long pulse operation of broadband ArF lasers have been sporadic, with the conclusion that practical long pulse ArF lasers were not feasible. Further challenges for long pulse operation arise from high intra-cavity losses induced by line-narrowing schemes, which are required for microlithography.

2. Electrical excitation circuit

In the past, several excitation schemes, most importantly spiker-sustainer excitation, have been developed to increase the pulse duration of excimer lasers. Unfortunately, these techniques are not well suited for spectrally narrowed lasers. Line-narrowed lasers require intracavity spectral selection components, which typically introduce 50% losses per cavity round trip in addition to the losses by the output coupling. In order to initiate and sustain lasing line-narrowed lasers require relatively high gain, which is not available from the stretched out excitation by spiker-sustainer systems. We demonstrate a novel excitation technique (patent pending), which provides extended laser pulse duration by means of dual pulse pumping.

The system makes use of the voltage gain afforded by a peaking capacitor Cp, which is smaller than the storage capacitor Cp-1 (fig. 1). Such systems are well known when operated in the two extreme configurations. In case 1 almost all energy is transferred to the peaking capacitor and the voltage gain is used only to reduce voltage stress on the switching element. Lasing occurs on the discharge fed by the peaking capacitor Cp. In the second case the peaking capacitor is very small and only stores enough energy to initiate a stable discharge. The main discharge and lasing is then driven off the storage capacitor Cp-1. Since gas breakdown is handled by the peaking capacitor Cp, Cp-1 can be charged to a lower voltage closer to twice the steady-state discharge voltage and thus attains a more stable discharge and higher efficiency. This is basically a simplified version of the spiker-sustainer excitation, but without the complexity of two separate systems. Such a system was realized for a broadband laser and yielded pulses with an integral square duration of 73ns at an energy of 27mJ. Figure 2 displays the temporal pulse shape of the broadband laser

In the interest of extended pulse duration for a line-narrowed laser an intermediate setting for Cp was chosen. In this configuration the amount of energy stored in Cp and Cp-1 at the instant of gas break down is about equal and two closely spaced pulses are generated. The ratio between the two pulses depends upon the size of the peaking capacitor, the total gas pressure and the fluorine partial pressure. The dependence of the temporal profile on the fluorine pressure is plotted in figure 3. The longest pulse duration is achieved when the two pulses contain about the same amount of energy. If the electrical excitation system is configured correctly, the maximum pulse duration and energy will be attained at the same fluorine partial pressure. This is in sharp contrast to classical short-pulse lasers, where, in the interest of longer pulse duration and narrower

linewidth, the fluorine pressure needs to be leaned-out relative to the maximum efficiency point.

3. Laser performance

The Tis pulse duration recorded for a burst at 2 kHz rep-rate at constant energy of 5 mJ is displayed in figure 4. The pulse duration is very stable and stays slightly above 40 ns for the entire burst. The laser was optimized to provide a best balance for all lithography relevant laser parameters. 50 ns pulses at 2 kHz are possible if the laser is optimized for pulse duration only. For comparison also data for a standard laser are shown, which indicates a pulse duration of about 25 ns. The dependence of the pulse energy at 2kHz for both the pulse-stretched and the standard laser on capacitor charging voltage is plotted in figure 5. In long pulse operation the same energy range is available, although higher charging voltages are required. As can be seen in figure 6 the Tis pulse duration is insensitive to changes in charging voltage and thus also to pulse energy. Both temporal intensity peaks rise and fall synchronously for different charging voltages.

One of the most important factors for cost of operation is the chamber lifetime. From previous experience, chamber lifetime can be predicted from the fluorine consumption and from the amount of energy over-head over the nominal operating energy. The long pulse laser exhibited the same fluorine consumption as a conventional laser. Figure 7 displays the voltage required to maintain a constant energy of 5 mJ over 45 million pulses. Clearly visible are the fluorine injections. Although the operating voltage of the long pulse laser was higher, the amount of fluorine consumed was identical to that of a standard laser. From this observation, together with the energy over-head shown in figure 5, it can be expected that the cost of operation of a long pulse laser closely follows that of a standard laser. However, longer pulses will be beneficial for the optics lifetime in the stepper.

The long pulse laser provided a dose stability at 2 kHz of 0.28% in an 80 pulse window. The stability is satisfactory, especially considering that a 3 billion shots old chamber was used for these measurements. However, compared to a short pulse laser energy fluctuations are increased by about 50% in long pulse operation (fig. 8). This behavior can be understood from observing the evolution of the temporal pulse shape during a burst (fig. 9). The first intensity peak in the pulse, which is equivalent to a standard laser, remains very stable during the burst. The second peak however is much more susceptible to repetition rate effects and causes an energy instability. Any instability in the discharge takes a certain time to develop and therefore affects a long pulse much more than a short one.

Nevertheless, in preliminary experiments the pulse-stretching excitation system has been able to generate 40 ns long pulses even at 4 kHz repetition rate (fig. 10). The presented pulse-stretching technique is therefore scalable to next generation lasers. In slightly modified configuration the pulse stretching system was also applied to the molecular fluorine laser and yielded laser pulses of 36 ns duration (fig. 11). This is insofar remarkable as the F_2 laser is generally believed to be self-terminating due to its bound lower laser level and thus does not lend itself easily to long pulse operation.

4. Conclusions

A novel excitation circuit was developed that greatly increases the pulse duration of line-narrowed excimer lasers. This was achieved without increasing system complexity and therefore the same high reliability of Cymer's conventionally excited lasers is maintained. The pulse-stretched laser yields the same fluorine consumption and pulse energy as a standard laser, albeit at somewhat higher charging voltages. Based on this, an equal chamber lifetime and cost of operation can be expected in long pulse operation. At 2kHz repetition rate a Tis pulse duration of 40ns was obtained, which was stable over the range of operating parameters. The longer pulse duration results in a reduction of the linewidth by approximately 0.05pm in FWHM and 0.1pm in the 95% integral. The primary trade-off for pulse-stretched operation is an increase in energy fluctuations by about 50%.

Acknowledgements

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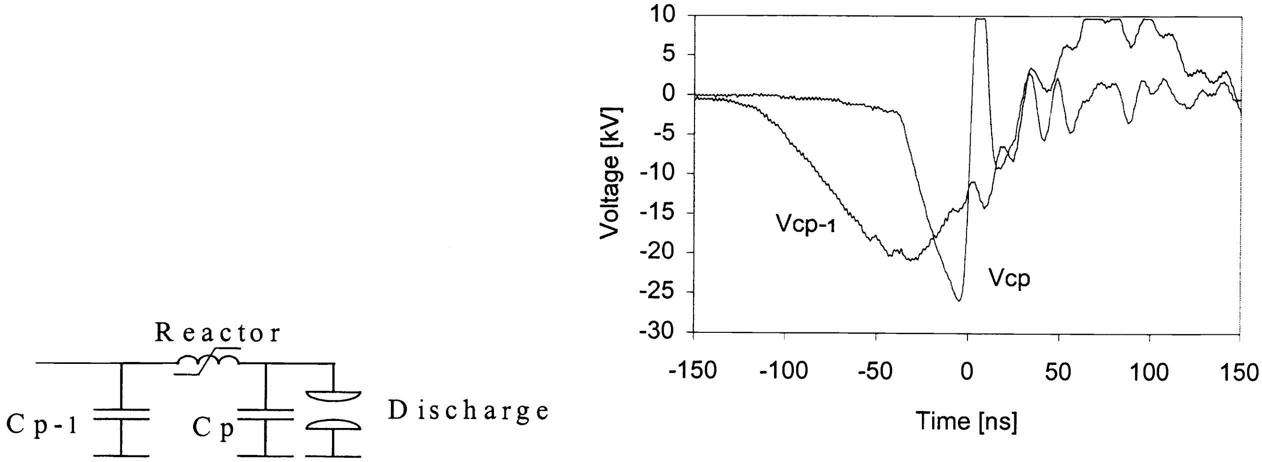

Figure 1. Circuit diagram and waveforms of simplified spiker-sustainer excitation

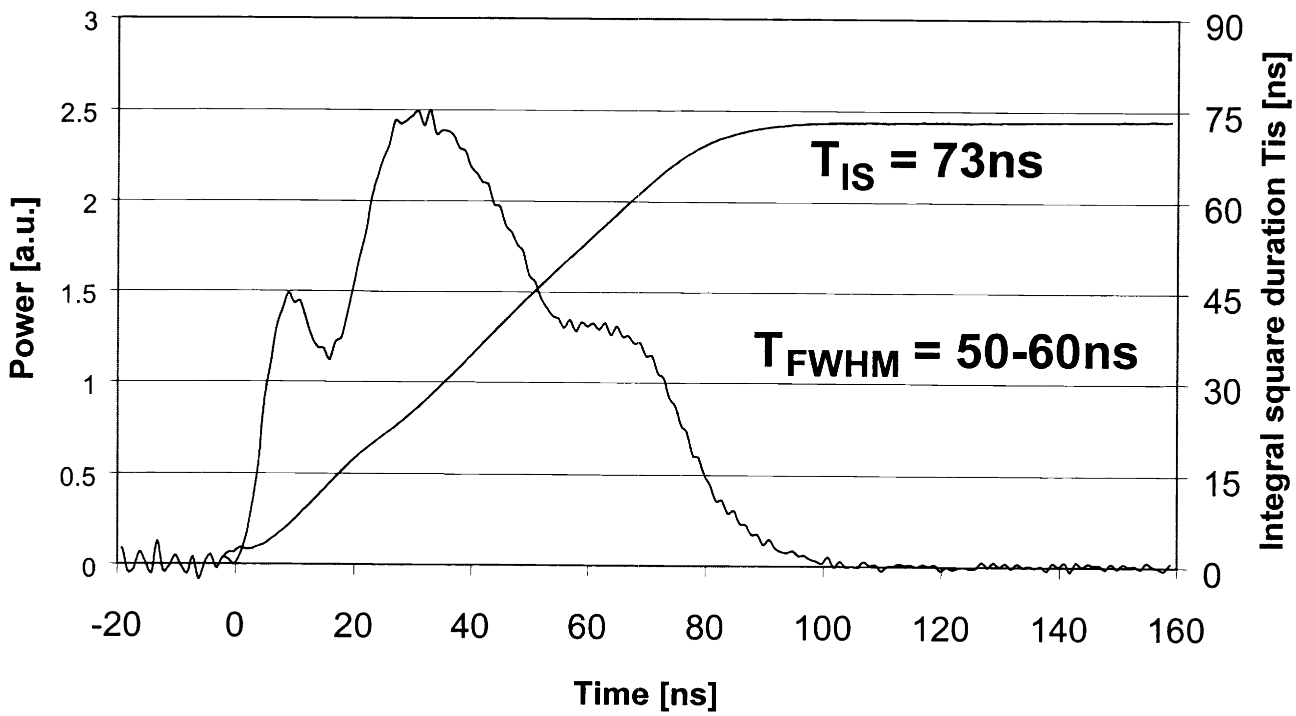

Figure 2. Temporal profile of a broadband ArF laser

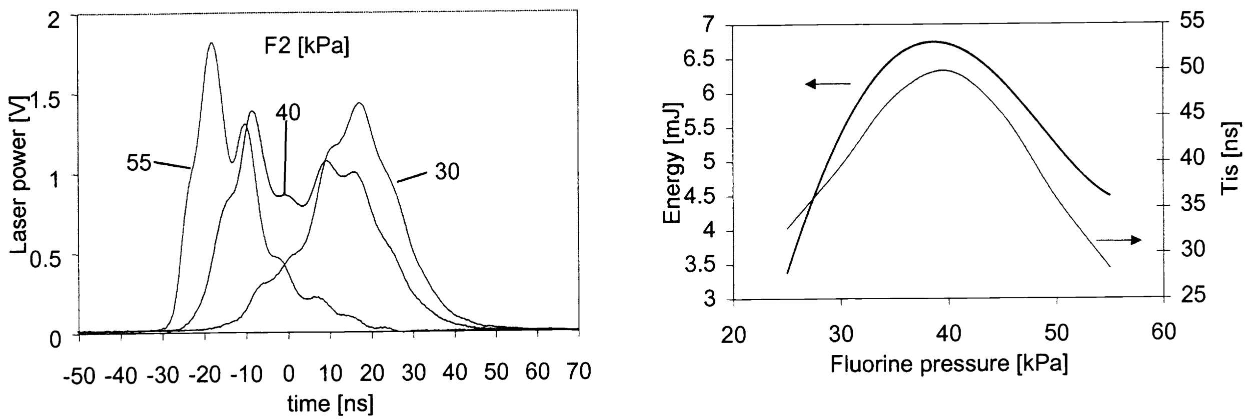

Figure 3. Dependence of the temporal profile on fluorine pressure

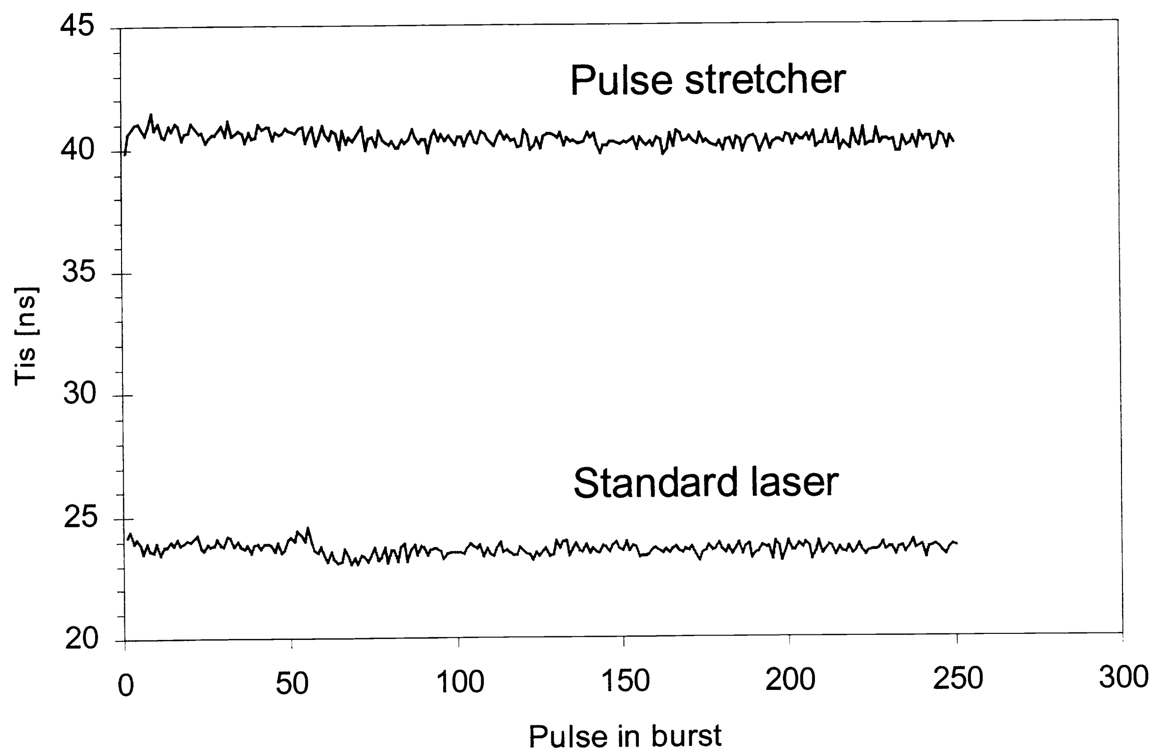

Figure 4. Evolution of the pulse duration in a 2 kHz burst

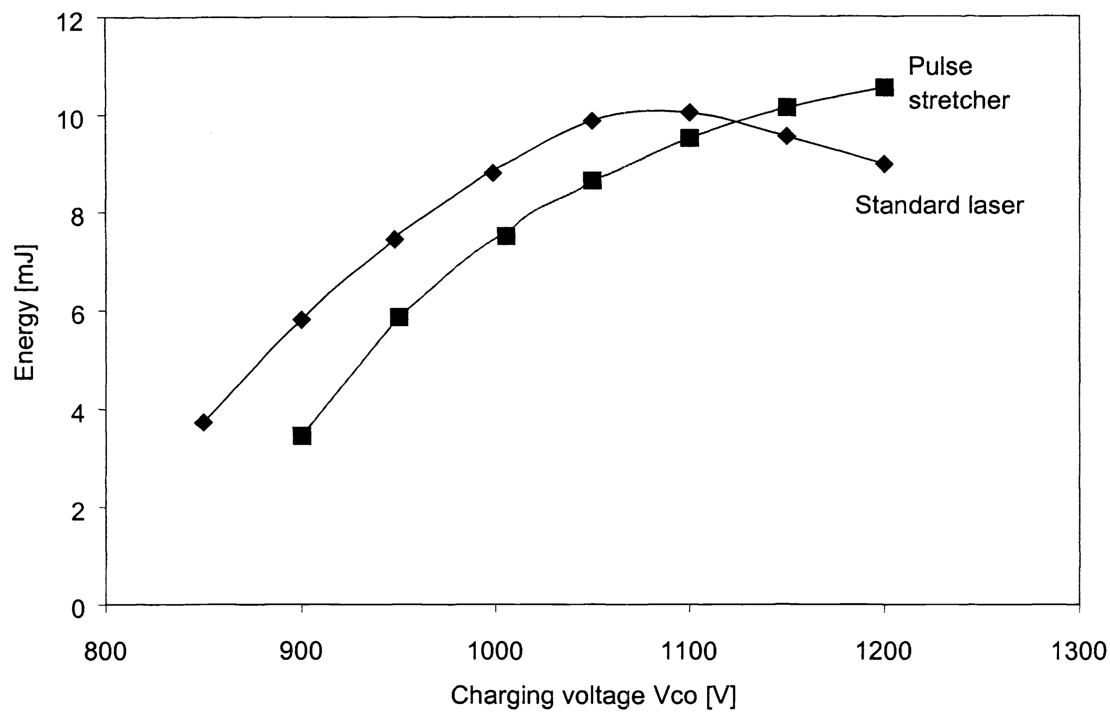

Figure 5. Dependence of the pulse energy on charging voltage

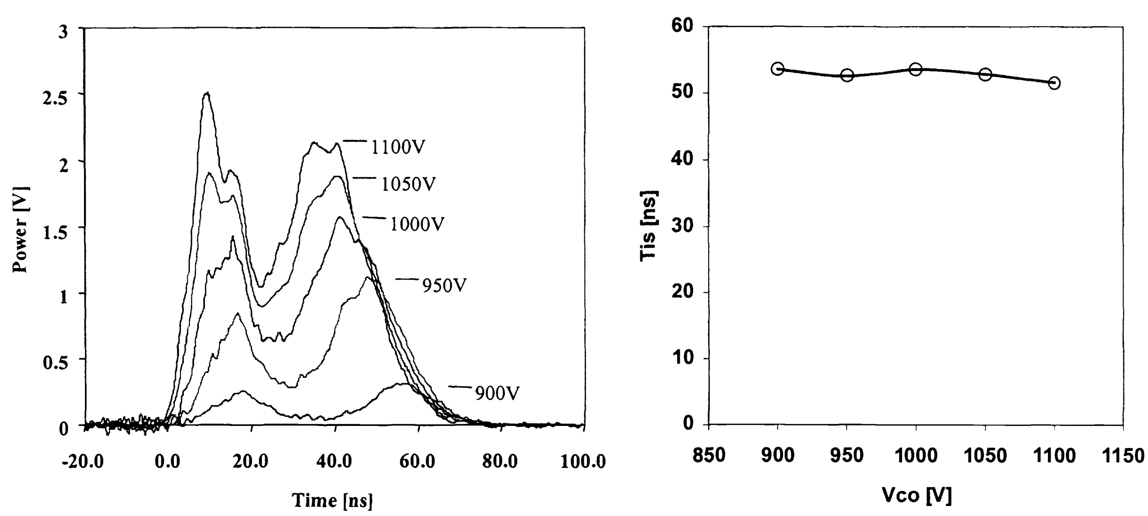

Figure 6 Dependence of the temporal profile and pulse duration on charging voltage.

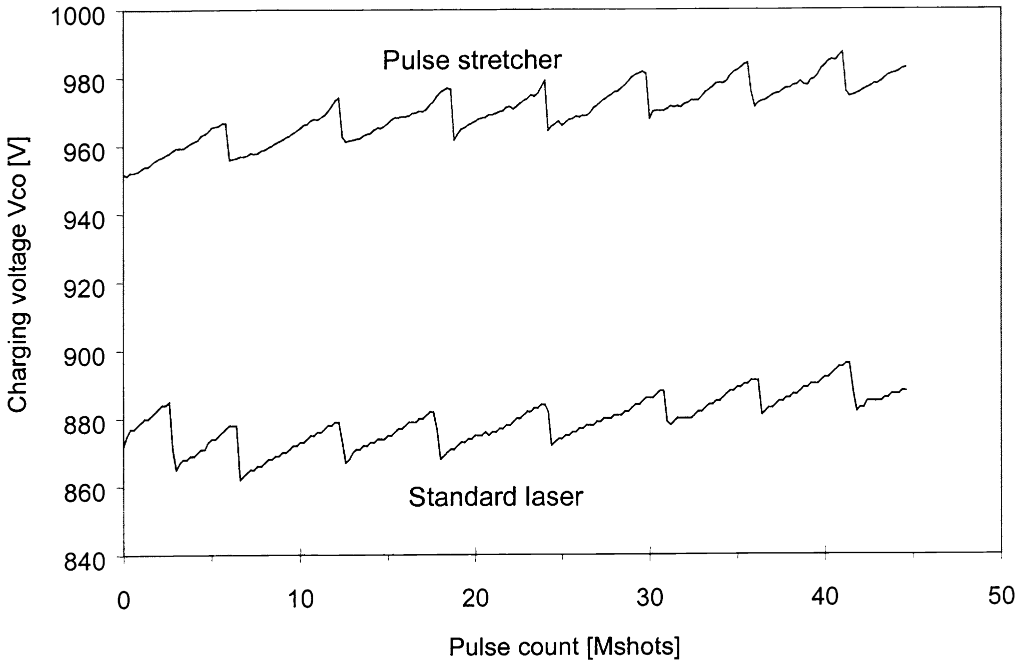

Figure 7 Comparing the fluorine injections required to maintain 5 mJ pulse energy for a pulse-stretched and a standard laser.

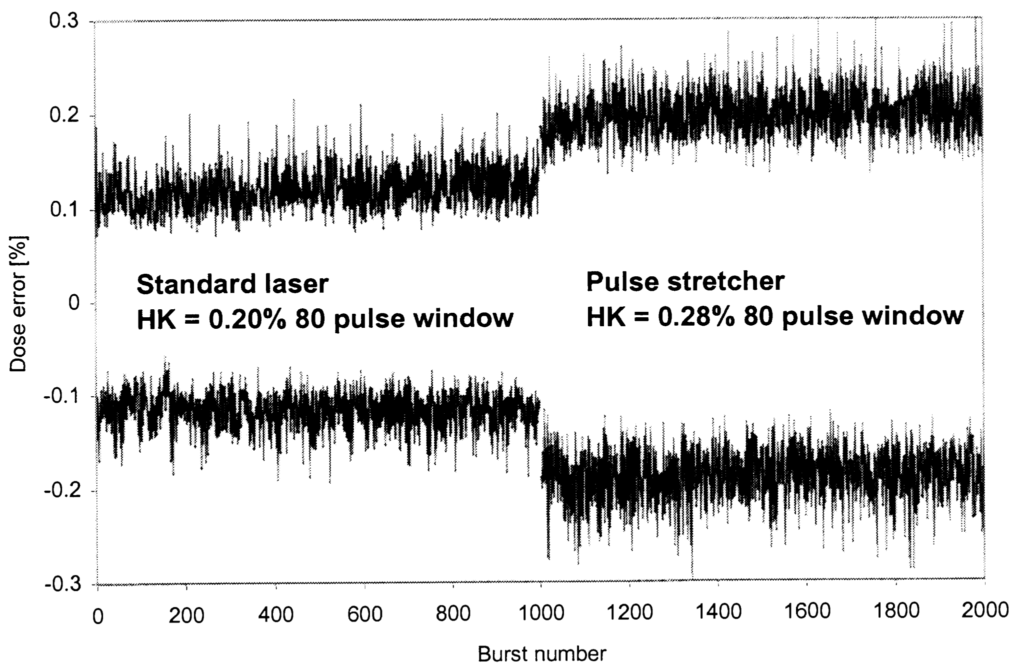

Figure 8. Comparison of the dose stability at 2 kHz of the standard and pulse stretched laser. The chamber had an age of 3 billion shots.

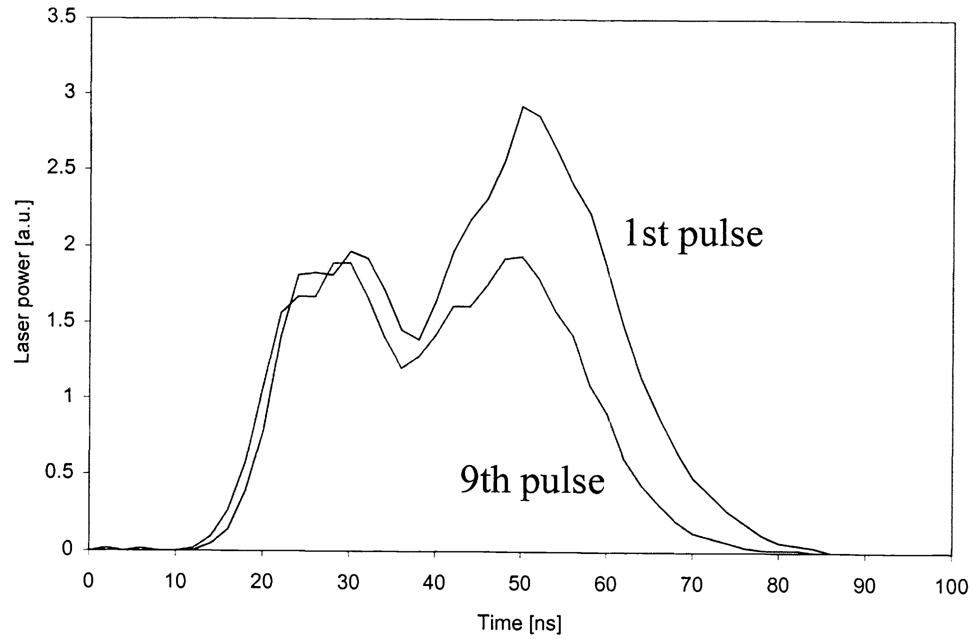

Figure 9 Comparison of the first and ninth pulse in a 2 kHz burst

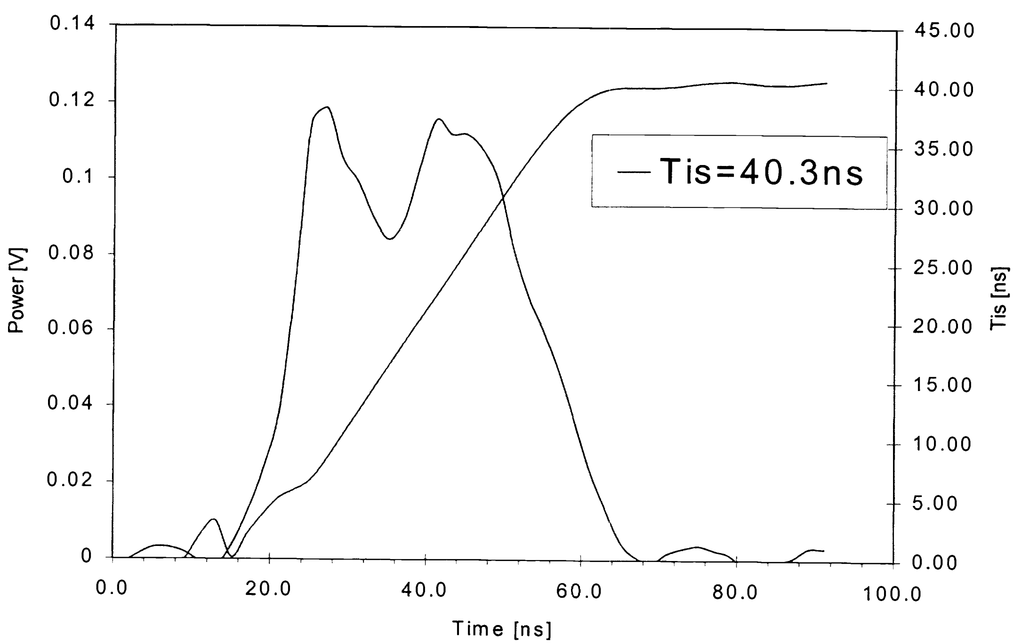

Figure 10 Temporal profile at 4 kHz repetition rate

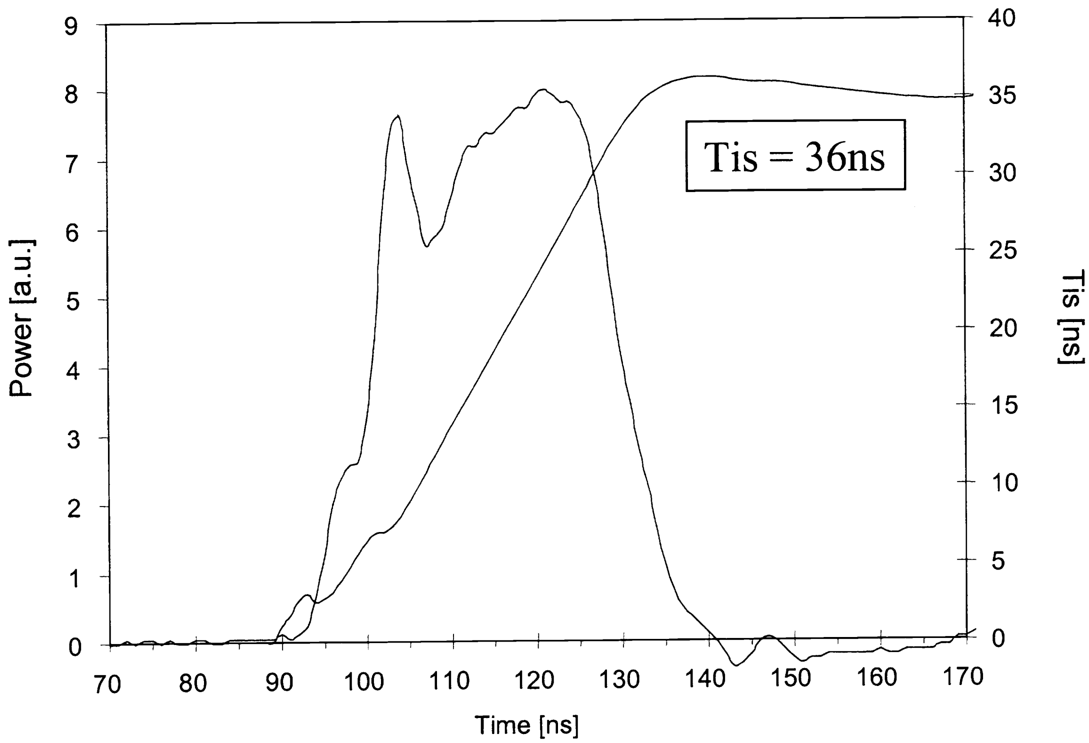

Figure 11 Temporal profile of the pulse stretched fluorine laser